The complexity of dust foreground emission in Cosmic Microwave Background maps

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Abstract: The study of angular fluctuations of the Cosmic Microwave Background 3-K radiation has become one of the cornerstones of current observational cosmology, as well as a major data pool for theorists in order to test cosmological models and fundamental physics theories. As the precision and angular resolution of CMB data sets get better, new challenges arise. One is to be able to accurately understand how far-infrared and microwave foreground emission from our Galaxy and extragalactic sources perturbate the observed CMB emission (these emissions are optically thin and add up to the cosmological signal). In particular, the diffuse dust emission from the Galaxy is complex and its spectral properties are still poorly known.
In this article, we describe the research on dust spectra which has been performed with the PRONAOS balloon-borne experiment, as well as other insights on dust spectral properties. Results show a clear dependence of the spectral emissivity on the temperature of the medium. The temperature itself varies a lot in both star-forming and quiet environments, so that taking into account temperature and spectral emissivity variations into dust models and templates for CMB data analysis is necessary. We propose a possible approach to build such a model to be used for next generation CMB experiment (e.g. Planck) component-separation analysis.

1. Introduction

Recent decades have seen a spectacular increase in the number of ground-based (e.g. DASI [1], QUAD [2], BICEP…), balloon-borne (e.g. BOOMERANG [3], MAXIMA [4], Archeops [5, 6]) and space-borne (COBE [7], WMAP [8], Planck [9]) Cosmic Microwave Background experiments. The reason for it is that the angular fluctuations in temperature and polarization of the Cosmic Microwave Background (CMB hereafter) contain a lot of cosmological information; in particular, the CMB fluctuations are directly shaped by the total density (Щ_0), the baryonic density (Щ_b) and the spectral index of the fluctuations. Polarization information allows to further discriminate between otherwise degenerated sets of parameters as well.
In this context, as the sensitivity and angular resolution of CMB experiments get better, new challenges arise. One is to be able to accurately understand how far-infrared and microwave foreground emission from our Galaxy and extragalactic sources perturbate the observed CMB emission (these emissions are optically thin and add up to the cosmological signal).
Notably, the diffuse dust emission from the Galaxy is complex and its spectral properties are still rather poorly known. The contamination of the diffuse dust emission in CMB maps is a rather serious issue, since it is diffused and polarized, and can be present at different ranges of temperatures. In the spectral range which is interesting for CMB analysis, the dust foreground emission is dominated by the large grain emission, at thermal equilibrium (e.g. [10]). Their submillimeter emission is characterized by a temperature (T) and a spectral dependence of the emissivity which is generally modeled by a simple spectral index (в).
The spectral index of a given dust grain population is directly linked to the internal physical mechanisms and the chemical nature of the grains. Although it is generally admitted from Kramers-Kцnig relations that 1 is a lower limit for the spectral index [11], a more famous and classically invoked value is 2, following the investigations of [12] and the calculations of e.g. [13]. This value is particularly invoked for isotropic crystalline grains, and it is sometimes thought to be an upper limit [14, 11]. For amorphous silicate or graphitic grains, a value of 2 is also favored for different physical reasons (e.g. [15]); however, it is not the case for amorphous carbon, which is thought to have a spectral index equal to 1 [16], as well as aggregates of silicates and graphite in a porous structure [17]. Silicate grains embedded in ice mantles are thought to have spectral indices between 1.5 and 2 [18, 19, 20, 21].
In general, amorphous rather than crystalline structure and increase of the grain size [22] are the main reasons to predict submillimeter spectral indices lower than 2.
Spectral indices above 2 may exist, according to several laboratory measurements on grain analogs [23, 15, 24, 25]. Also, [24] and [25] showed an anti-correlation existing for some types of grains between the temperature and the emissivity spectral index.

Observations of the diffuse interstellar medium at large scales tend to favor в around 2 (e.g. [26], [27]).
In the case of molecular clouds, spectral indices are usually found to be between 1.5 and 2, however low values (0.2-1.4) of the spectral index have been observed in circum-stellar environments. This can be attributed to grain growth in dense stellar envelopes. Low indices have also been observed in molecular cloud cores (e.g. [28]).
Spectral indices larger than 2 have also been observed in the millimeter range [29, 30, 31], in particular on the whole sky at large scales by the WMAP satellite [32].

In this context, submillimeter multi-band imaging of the interstellar medium provides a lot of useful information about dust properties and interstellar medium structure, especially if the dust emission parameters, namely both the temperature and the spectral index, can be properly derived on top of submillimeter intensities. This has been done by the PRONAOS balloon-borne experiment.

2. PRONAOS results on the temperature – spectral index dependence

PRONAOS (PROgramme NAtional d'Observations Submillimиtriques, [33]) is a submillimeter balloon-borne experiment. Four bolometers cooled at 0.3 K measure the submillimeter flux with sensitivity to low brightness gradients of about 4 MJy/sr in band 1 (200 мm) and 0.8 MJy/sr in band 4 (580 мm). The effective wavelengths are 200, 260, 360 and 580 мm, and the angular resolutions are 2' in bands 1 and 2, 2.5' in band 3 and 3.5' in band 4. This experiment has observed various phases of the interstellar medium, from diffuse clouds in Polaris [34] and Taurus [35] to massive star-forming regions in Orion [36, 37], Messier 17 [38] and Cygnus B. The с Ophiuchi low-mass star-forming region has also been observed, as well as the edge-on spiral galaxy NGC 891 [39].
[40] have analyzed the constraints that PRONAOS data establish on the dust spectral index and its relation to the temperature. Using mostly PRONAOS and IRAS data, they fit a modified black body law to the spectra:

$$I_н = e_0 \, B_н(л, T) \, (л/л_0)^{-в} \qquad \text{(eq. 1)}$$

where $I_н$ is the spectral intensity (MJy/sr), e_0 is the emissivity at $л_0$ of the observed dust column density, $B_н$ is the Planck function, T is the temperature and в is the spectral index.
[34, 36] gave tentative evidences of a spectral index larger than 2, respectively in Orion and the Polaris flare. [37, 38] gave good evidence of large variations of the spectral index, including values above 2, and the presence of an anticorrelation between the temperature and the spectral index in massive star-forming regions. In order to generalize these findings to more regions of the interstellar medium, [40] used most available data from PRONAOS and other data from far-infrared and submillimeter experiments.
The anti-correlation between the temperature and the spectral index is found for all observed dusty environments which exhibit a relatively wide range of temperatures. Remarkably, data points from other regions also fit well into the general scheme (see Fig. 1). An example of maps of the temperature and the spectral index is shown in Fig. 2 for M17.

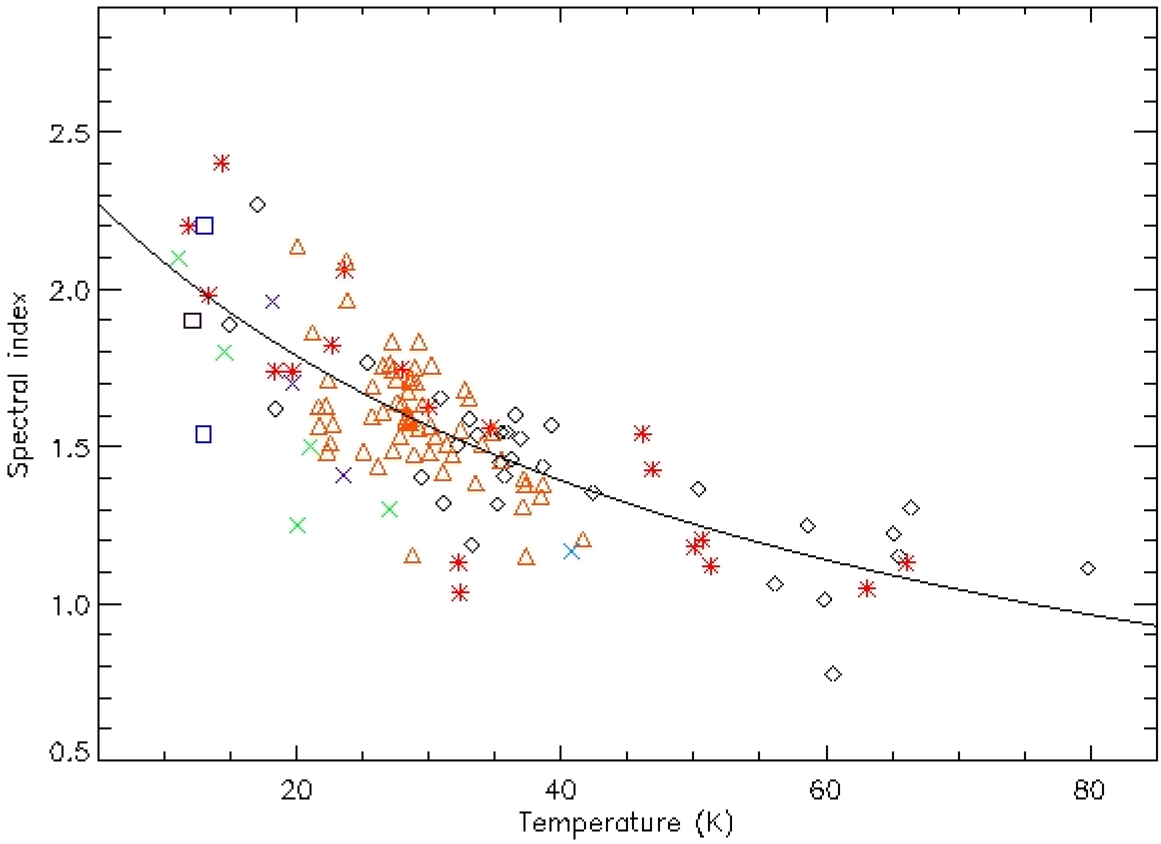

Figure 1: temperature (K) – spectral index anti-correlation from PRONAOS data. Figure from [40].

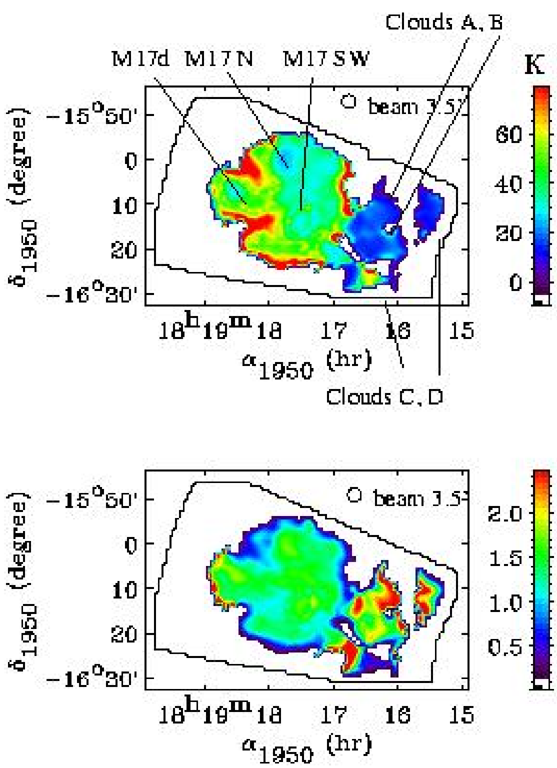

Figure 2: an example of temperature (top) and spectral index (bottom) maps in the M17 complex. Figure from [38].

It is notable that no data points with *T* > 35 K and в > 1.6 can be found, nor points with *T* < 20 K and в < 1.5. All cold regions below 18 K have spectral indices above 1.8, except one point which is compatible with a value above 1.8.
A hyperbolic fit of the data using: в = 1 / (д+щT), where д and щ are free parameters, considering that the temperature is the independent variable, gives

д = 0.40±0.02 and щ = 0.0079±0.0005K−1,

with ч2/d.o.f. = 120/120. The temperature dependence of the emissivity spectral index is thus very well fitted with an hyperbolic approximating function.

3. Recent Archeops results on dust properties

Recently, [41] have analyzed Archeops Galactic point-source data and found that an anti-correlation was present between the temperature and the spectral index (see Fig. 3).

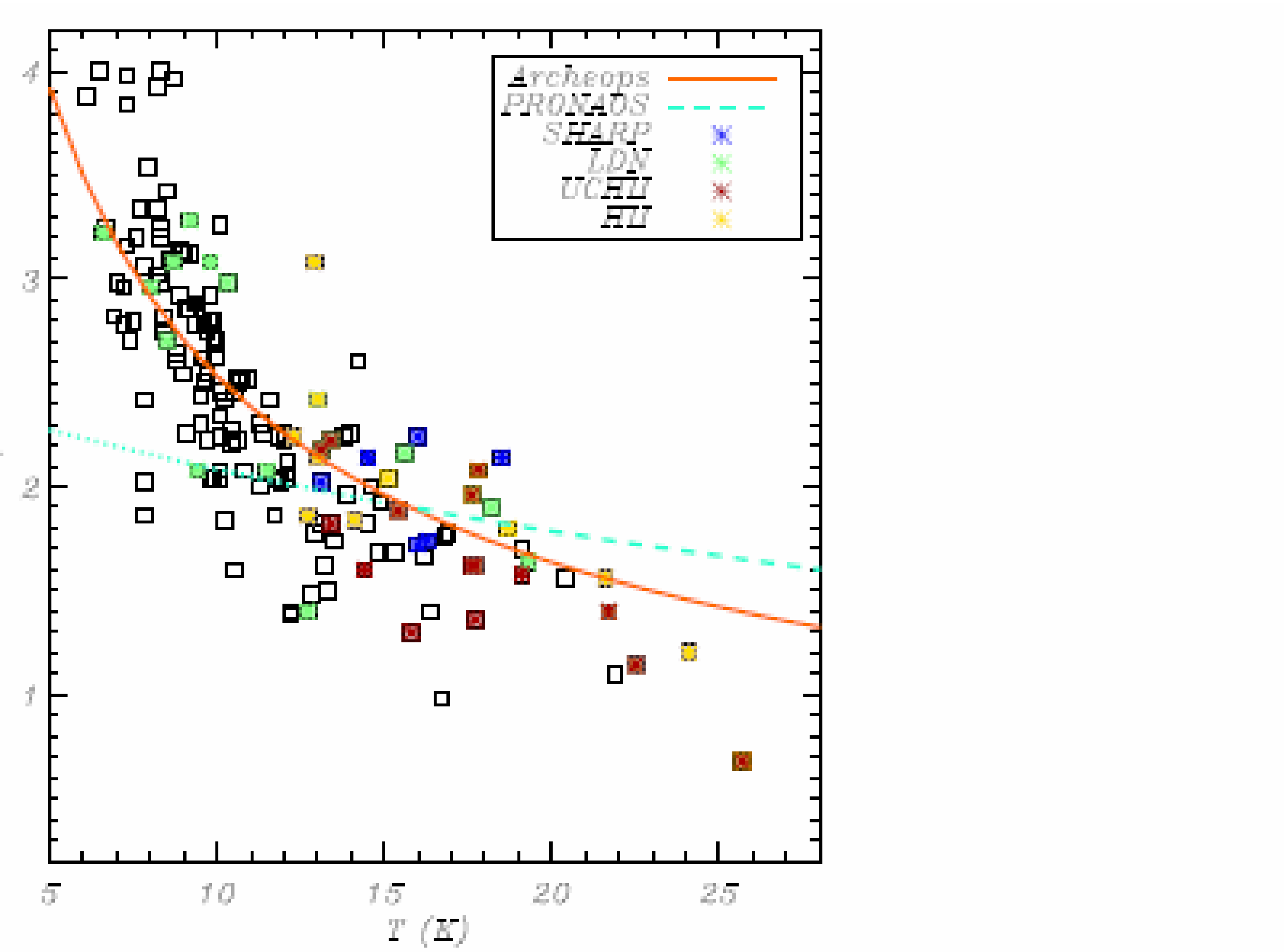

Figure 3: Temperature – spectral index anti-correlation as seen with Archeops point sources (from [41])

It is interesting to see that the Dйsert et al. law which is fitted to the Archeops data is significantly steeper than the Dupac et al. law [40] fitted to the PRONAOS data. In fact, such a difference is hardly surprising since Archeops observes at longer wavelengths than PRONAOS does. Dust grain properties may change enough throughout the submillimeter / millimeter range so that the anti-correlation effect is significantly different for the two experiments.

4. Discussion of the temperature – spectral index anti-correlation effect

The Archeops results [41] have been a very welcome confirmation of the surprising effect discovered by PRONAOS [37, 38, 40]. One can however say that there are different possible explanations for this effect, which we try to summarize below.
Mixtures of dust components with different temperatures, but having the same spectral index, can be put forward to explain apparent low indices. However, this effect was shown to be small compared to the amplitude of the observed spectral index variations [38].
Low indices have been observed in active environments such as circumstellar disks and warm molecular cloud cores. PRONAOS observations of Orion, M17, Cygnus B and с Ophiuchi show such low spectral indices around 1. This could be due to the increase of the grain size in dense environments [18], whose models with different grain size distributions show that the maximum grain radius adopted is crucial for the long-wavelength emissivity slope. This is also the reason invoked by [42] to explain their results, which showed an inverse dependence of the spectral index on the optical depth.
However, we do not find such correlation in our data. Moreover, the range of variations that they find for the spectral index (from 1.6 to 3.2) is significantly different from ours (from 1 to 2.4), though with a similar variation amplitude. Also, these grain growth effects are invoked for very peculiar dense environments around stars rather than for large scale observations such as the PRONAOS ones. Therefore, it is difficult to consider that size distribution effects are dominant in the T - в anti-correlation that we observe, though they may play a role.
Another slightly different explanation could be that one finds different chemical composition or physical state of the grains following the physical conditions of the medium, in particular following the temperature. Cold environments could harbor fluffy silicate grains including ice compounds, having spectral indices of 2 [20], or simply silicate or graphitic particles [13], or even olivine core or fused quartz grains with ice mantles ([43], в ~ 3) to explain high indices above 2. Warm regions could harbor aggregates of silicates, porous graphite or amorphous carbon and therefore have a spectral index around 1 [17]. Nevertheless, more observations are needed to constrain the chemical structure of the large grains in various media and confirm this hypothesis.
Finally, an explanation may be searched for in a temperature dependence of the intrinsic optical properties of the grains (see [44] for a review of the different physical processes). This can be linked to laboratory results [24, 25] which showed a T - в anti-correlation on interstellar grain analogs. This hypothesis has been recently investigated by [45], who demonstrate that it is possible to explain the temperature – spectral index dependence by incorporating the effect of the disordered internal structure of amorphous dust grains. However, the range of parameters to be tuned is large, and many different effects can play a role, which may result in many very different emissivity characteristics for the dust grains.
To summarize, all these possible explanations are still valid and it would require very accurate spectro-photometry on the different phases of the interstellar medium to be able to discriminate between them.

5. Consequences for dust models in CMB data analysis

While the Archeops result may be more accurate for Cosmic Microwave Background data analysis because it has been observed at longer wavelengths than the PRONAOS one, the PRONAOS effect is still very useful to study because it gives an insight on how variable this effect may be depending on the wavelength range we consider, as well as the interstellar medium environment. These complex properties of the dust emissivity allow very different spectral energy distributions to take place in foreground emissions, as Fig. 4 shows. Therefore, it is important to take into account these properties as accurately as possible when separating the dust foreground from Cosmic Microwave Background maps.
The first step to work on in these matters could be to combine both data sets in such a way that actual data at all different wavelengths (from 200 мм to the millimeter range) are studied in order to see better details in the spectral energy distribution than just a single spectral index. Using far-infrared IRAS data for instance would also help to discriminate between different possible populations of dust grains with different temperatures. When a relatively accurate description of the spectral indices with respect to temperature and wavelength range is reached, building a dust model and dust template maps for CMB data analysis can be done with the following steps:

- establishing a set of analytical equations which describe в as a function of T and л
- using the adequate set of far-infrared maps to be used as the basis for extrapolation to CMB frequencies (e.g. Planck frequencies are 30, 44, 70, 100, 143, 217, 353, 545, 857 GHz)
- extrapolating these maps to create the new template maps at CMB frequencies from the в (T, л) equations

- fine-tuning the angular structure of the new template maps using correlation with other measurements
- re-calculating the temperature and spectral indices from the newly-made template maps and compare to the model
- (maybe) iteratively refine the model and the template maps

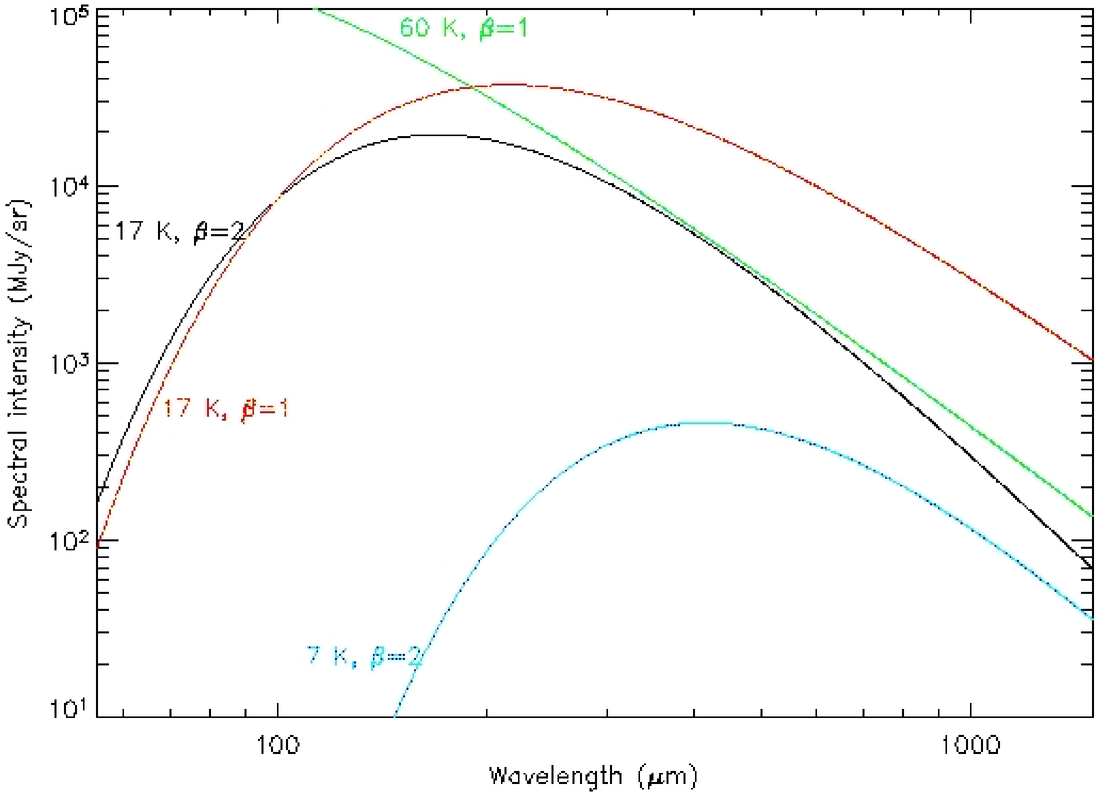

Figure 4: Dust spectral energy distribution for populations of dust grains at 60 K with $\beta = 1$ (top, green), T = 17 K, $\beta = 1$ (red), 17 K, $\beta = 2$ (black) and 7 K, $\beta = 2$ (bottom, blue). At 1 mm and beyond (CMB wavelengths), the differences in spectral energy distribution slope can be clearly seen.

Of course, such a model would not be the definitive model to use for e.g. CMB component-separation analysis, but it would be an interesting step to take into account more realistic dust foreground properties than that currently in use. In general, CMB component-separation specialists should keep in mind that the emissivity of the dust in the submillimeter / millimeter / centimeter domains is complex and still not very well known. The polarization properties of Galactic dust are another plausible can of worms for precision cosmology in the field of the Cosmic Microwave Background studies. The corresponding polarization properties in terms of spectral energy distribution of the dust are still basically unknown, and from what we can observe for the intensity aspect of the problem, the polarization properties might as well be quite complex and difficult to predict. As for intensity, accurate measurements of the polarized dust emission are now needed to increase our knowledge on the polarized emissivity of the dust. The balloon-borne project PILOT [46] will help in resolving these issues.

6. Conclusion

We have presented some recent insights on dust emissivity properties, which we studied from PRONAOS data mainly. The results show that it is risky to assume that the dust foreground emission in CMB maps is well known and well modeled by a single spectral energy distribution throughout a whole-sky map. Such an assumption may be sufficient for past CMB data sets, however it is unlikely that it will be for future very accurate ones, notably because the polarization properties are also difficult to understand.

In this context, a serious and thorough study of the dust emissivity properties in the various phases of the interstellar medium is needed in order to know better how the interstellar medium works and be able to separate components with precision in CMB data sets.

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